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Grid-Connected Distributed Wind-Photovoltaic Energy Management: A Review

Sasmita Behera and Bibhuti Bhusan Pati

Abstract

Energy management comprises of the planning, operation and control of both energy production and its demand. The wind energy availability is site-specific, time-dependent and nondispatchable. As the use of electricity is growing and conventional sources are depleting, the major renewable sources, like wind and photovoltaic (PV), have increased their share in the generation mix. The best possible resource utilization, having a track of load and renewable resource forecast, assures significant reduction of the net cost of the operation. Modular hybrid energy systems with some storage as back up near load center change the scenario of unidirectional power flow to bidirectional with the distributed generation. The performance of such systems can be enhanced by the accomplishment of advanced control schemes in a centralized system controller or distributed control. In grid-connected mode, these can support the grid to tackle power quality issues, which optimize the use of the renewable resource. The chapter aims to bring recent trends with changing requirements due to distributed generation (DG), summarizing the research works done in the last 10 years with some vision of future trends.

Keywords: distributed generation, energy management, forecast, control, grid-connected

1. Introduction

A renewable hybrid energy system comprises of a couple of energy sources, a power conditioning device, a controller and sometimes with an energy storage system. When such renewable energy sources (RES) are integrated to the grid, variable output due to the stochastic nature of input may lead to instability and power quality issues [1]. In this changing scenario, micro-grids (MGs) have come up as a solution to maintain power supply in small scale as an autonomous entity in the event of grid failure. It has complementing resources or different DG sources in combination with storage with power electronic interface. Distributed energy resource (DER) can be either a distributed generator or distributed energy storage. Under its spectrum, it can be PV, wind, heat pumps, combined heat and power (CHP) generation, energy storage (ES), fuel cells (FCs), electric vehicles (EVs), energy efficiency (EE) and demand response (DR). The behavior of the resources, such as EE, DR, heat pumps, and EVs, is user dependent. Further, the PV source has no inertia. So ES and FCs can provide more reliability and flexibility to the grid

if operated in a manner coincident with grid needs that respect storage limitations. These DGs have made the grid more resilient, efficient, environment-friendly, flexible, less vulnerable, easier to control, immune to issues at some other location, slow gradual capital investment, integrating to grid with minimal disturbance to existing loads during commencing. Participation of DERs in operation is profitable in respect of load shifting without grid up-gradation curtails peak demand, grid support by storage responding to demand thereby improving frequency response reducing spinning reserve. EVs and MGs can provide ancillary services. Under normal operation of the grid, varying capabilities of the DERs support voltage and reactive power whereas under fault voltage and frequency ride through capability is expected. Under such fault, the inverter must respond as per requirement. With the coordination of inverter-based resources in a group, it is possible that the DERs counteract to grid contingencies such as voltage and frequency deviations, and assist in fast recovery. So they are termed virtual inertia. But, at the same time, some issues are of concern and have drawn the attention of researchers. They are mainly due to stochastic nature such as load following, power vs. energy profile in storage, stability, reliability, cost, control architecture, autonomous control, power quality issues and grid interconnection. Considering these issues, in [2] the feasibility study, the unit commitment for reliable power supply and modeling of energy systems of PV, wind and diesel generator are focused. In the past decade, more significant development has taken place with various combinations of sources and storage. Optimization in all respect of wind energy for grid integration has been thoroughly reviewed [3] and observed to have good success. The control topology and the objectives have also changed in recent years. In addition to other reviews, control aspects and reliability issues with such sources are discussed [4]. The application of evolutionary technique and game theory in hybrid renewable energy is also presented. The chapter revisits the changing requirements due to DG, summarizing the research works done in the last 10 years with some vision of future trends.

2. Regulatory, project finance and technical perspective

The renewable electricity demand is predicted to add up 20% more within the next 5 years. They can have the quickest development within the power sector, providing nearly 1/3rd of the requirement in 2023 [5]. Further, there is forecast to exceed 70% of world electricity produced, primarily by PV and followed by wind, hydropower, and bio-energy. Hydropower remains the biggest such supply, meeting 16% of the world electricity demand by 2023, followed by wind (6%), PV (4%), and bio-energy (3%). Energy storage for grid applications lacks a sufficient regulatory history.

Whereas active regulation of voltage was not permitted and the DERs had to trip on abnormal voltage or frequency, participation in voltage and frequency control was desirable due to a gradual increase of the percentage of DER in power system. This was resolved in 2003. The first amendment to this came after a decade (11 years) but the second one came just after 4 years of first [6]. This comes in line with the steeper increase of DER penetration than the previous decade. As the DER are geographically dispersed, the communication interface between DER and the main grid and in between the DERs has been an additional demand of the hour for smooth and reliable coordinated control.

Some of the distribution grid safety demands are (1) short trip times, (2) ride-through with momentary cessation (3) voltage rise concerns (4) protection coordination (5) islanding concerns for the safety of workers. Bulk system reliability demands (1) long trip times (2) ride-through without momentary cessation (3) reactive power support.

Increasing penetration of unconventional generation to grid is reducing system inertia which can degrade system frequency stability. So, active power output is modulated in response to frequency deviation (Default droop 0.05 p.u. frequency for 1 p.u. active power change).

Voltage benchmarks standard for voltage fluctuations is within $\pm 5\%$ at customer end. As a DER exports active power, voltage rises and the profile is disturbed and quality is compromised.

Current grid standards massively need that low-power KW range single-phase PV systems supply at unity power factor with maximum power point tracking (MPPT), and detect fault and island from the grid in such situation [7]. However loss of these generations under grid faults gives rise to voltage flickers, power outages, and an unstable system. So grid code amendments for increased entry of PV systems in the distribution grid are expected. The standards have undergone a significant review for low-tension interconnection in many countries. Also, reactive power can be supported either by changing the tap setting of the transformer or by the PV inverters with advanced control strategies to maintain the grid voltage.

Investments in RES for utility are normally assessed from regulatory, project finance, and technical perspectives. The regulatory requirement is satisfied by utility compliance as well as reduction of the associated cost. The budget estimate looks at the investment and benefits of the particular project. The technical assessment deeply goes through the safety concern of the specific technology involved and its operation. Besides these project specific assessments for RES, physical benefits of transmission and storage and the effect in the integrated picture of the grid is also important. It is therefore always recommended to go for an integrated approach for full exploitation of renewable generation and electricity storage with respect to transmission and distribution [8]. And this in line with the state utility cannot be undermined also. It is further recommended at all levels to increase its research and development (R&D) in basic electrochemistry to find out the materials and discover the electrochemical technology suitable for use in grid. Department of energy, of concerned countries, have been leading the R&D to deal with reliability, resilience, cyber security, and affordability issues from the grid modernization perspective.

3. Weather-dependent variability of renewable resources

The wind energy and PV are expected to have a lion's share in the prospect of the power utility. So, the future energy source is pivoted on the in-depth realization of their variability. Resource variability is a multi-faceted notion expressed by a range of distinctive characteristics. Simultaneously, research to date tells that there is restricted knowledge about the variability of the future power system. The variable attribute of climatic fluctuations is the reason of inconsistency of the RES and creates uncertainty in the energy production on the range of seconds, hours and days even. It is estimated that clouds limit up to 70% of daylight hour solar energy potential. Grid sometimes deals with aggregation over massive areas and this mitigates the variability of every single RES.

Presently a large variation is tackled via switching in fast-acting conventional sources depending on the climate forecasts on a minute-by-minute and hourly basis. Such variability can additionally be taken care by setting up large scale storage on the grid or; by the long-distance transmission of RE linking to larger pools of such generations in order to equalize regional surplus or shortfall nearby in future. Graabak et al. [9] have addressed the variability characteristics such as: (i) Distribution long term, (ii) distribution short term, (iii) step changes, (iv) autocorrelation, (v) spatial-correlation, (vi) cross-correlation and (vi) predictable pattern.

Distribution can be short-term (minutes, less than 1 h) or long-term (1 h or more). These terminologies carry their own implication.

Many such related papers refer to “step changes” as a variability characteristic. These are the alteration in the available resource that takes place in small time steps of minutes to some hours. Another variable characteristic is autocorrelation [10] which figures out the statistical relation among values of the same parameter in a series. The relationship of wind speed information between different locations and the corresponding relationship of solar irradiance for different locations are under study by several projects. This spatial correlation is perceived as one of the instrument to gauge variability characteristics. Wind and solar sources may also show one kind of diurnal and seasonal trends.

Power from sun, wind, and ocean additionally exhibit predictable seasonal patterns recognized as a distinguishing variability characteristic. Pattern forecast for this trend of wind and sun is complicated, and it is a subject matter taken up in many papers. In a precise study, Tande et al. [11] have viewed reanalysis data set for illustrating of wind variability characteristics. With information of a temporal resolution of 6 h and a spatial resolution of 2.5° in each latitude and longitude, a two-dimensional linear interpolation of neighboring locations is utilized to get wind speeds at the chosen sites. Both offshore and onshore information can be dealt with in this way for explaining the variability. It is apparent that entry of offshore wind generation and its variability will noticeably affect the grid.

In the study performed by Wiemken et al. [12] record from 1995 extracted from 100 monitored PV systems (rooftop plants 1–5 kW) with a 5 min time resolution ensembled for 243 kW (grid connected) is used. A model is developed taking onshore wind and PV energy generation for the period 2001–2011 across 27 nations in Europe. The data is taken from NASA for hourly values of wind speed and solar irradiance documented at a spatial resolution of 0.5° E/W and 0.66° N/S. The generation from wind and PV translated from the climatic record were later on combined to structure regional or nation-specific datasets. The model first considered PV and wind sources to contribute half of the energy supply of total requirement. Further PV share in the wind/PV proportions of 0, 20, 40 and 60% are investigated.

4. Power generation forecasts

Contribution of wind energy has been the largest share out of the renewable energies and expects growth further. For responsible and sustainable growth of wind energy industry, reliability, robustness and stability are important factors. As wind energy integration to the grid is in MW scale, in future it may function as base load plant. So, the decision of economic load dispatch will largely be affected by proper forecasting of wind power. The objective is to improve accuracy in forecasting wind speed and power 1 day ahead so that it becomes reliable, which will be a benefit to the load dispatch centers as well as installation of additional wind turbines onshore and offshore.

Wind forecasting has been taken up in literature by various researchers. The forecasting for power may be very short term (within 2.5 s), short term (10 min to 1 h), long term (15 min to 3 h) or a day ahead (24 h). Forecasting wind speed is an important factor, based on which planning of new wind farm depends. Specifically for offshore wind farms, the safety requirement has less advanced. As wind speed prediction and power prediction takes time for computation and error in forecasting wind power 1 day ahead is more compared to the short term, there is a need for improvement. Research has shown good result from the hybrid method. The researchers are oriented to make wind power predictable. When the wind is

predictable, it becomes reliable, which will be a benefit to the load dispatch centers for economic load dispatch as well as the installation of additional wind turbines onshore and offshore.

Going through the available tools and the accuracy, the methods/prediction models are broadly divided into physical, statistical and artificial intelligence based methods [13]. Out of various statistical methods such as curve fitting, statistical approximation autoregressive integrated moving average (ARIMA), seasonal ARIMA, extrapolation with periodic function, methods of finding probability density functions (PDF) have been evaluated by the coefficient of determination [14]. Different software models have been developed such as WPMS, WPPT, Prediktor, ARMINES, Previento, Zephyr, AWPPS, Ewind, ANEMOS and adopted in different countries [15]. Some of them are hybrid methods. Prediction of offshore extreme wind is important for the protection of offshore wind system so that such sites can be avoided during planning. Method of independent storms (MIS) stands better as compared to the other three in the study by An et al. [16]. In another work, the extreme wind has been estimated by the combination of swarm optimization with the traditional methods which added improvement [17]. The available software has their limitations up to how many meteorological data required, precision in numerical weather prediction (NWP), different accuracy indices for short and long term prediction etc. Intelligent techniques such as Artificial Neural Network (ANN) [18], Fuzzy, Support Vector Machine (SVM), Wavelet, Hilbert-Huang transform, data mining techniques [19], swarm optimization combining the statistical methods of time series prediction with improvement in nonlinear node functions and training algorithms have given good results as compared to statistical/any method alone [19, 20]. Combination of Fuzzy and ANN take less prediction time thus gives faster result [21]. It has been remarked that grouping wind farms for wind forecasting can give better result [19]. Instead of predicting the wind speed exactly, prediction into lower and upper bounds method (LUBE) [22] in prediction interval with defined confidence level gives better result in performance indices. Wind speed has been estimated by RBF (radial basis function) neural network and wind turbine has been appropriately controlled for maximization of wind power [23]. "Anti-phase correlation" of wind speed and solar radiation has been found after wavelet analysis, implying that wind and solar energy can complement each other in generating electricity [24].

Smart grid performs also with penetration of PV and has to consolidate its performance figures in the presence of variability. Many researchers report on the novel hybrid intelligent algorithm for PV forecasting taking its fluctuating behavior. In this regard, wavelet transforms (WT), stochastic learning, remote sensing method and fuzzy ARTMAP (FA) network. Forecasting accurately improves system efficiency also.

As numerical prediction depends on weather data, which is provided by sensors, reduction of dependence on sensors for wind speed, rather estimation method of wind speed for sensor-less control is the need.

Different capacity of battery, wind, PV is considered to check which proportion of each component is economical for a specific location Dhahran in Saudi Arabia taking historical weather data during the demand of different months in a year for the wind-PV hybrid power system (WPVHPS) [25]. The addition of wind generation is more economical than PV. The addition of more battery can reduce the diesel generation and time of use.

Prediction is vital for energy management [26]. The energy management functions in a wind-battery system are to (1) charge the battery from wind (2) supply the load from wind power (3) trade the wind/battery power to the grid (4) buy power from grid and store in the battery or supply it to the load; and (5) supply the local load from battery. The day ahead electricity rate and wind energy are

forecasted through Wavelet-ARMA of time series breaking it into smooth subseries. The state of charge (SOC) of battery is predicted in a longer time horizon. In another case study of Turkey [27], based on 15 years of data of global solar radiation distribution, no relationship between the distribution of annual time lapse and solar energy and solar radiation intensity are established.

The solar and wind energy potential are surveyed for five sites in Corsica [28]. From this study, two sites with the desirable trait are chosen and the sizing and the economics for an isolated hybrid PV/wind systems are compared. The trend is dependent on site-specific resource analysis. The sites with more wind potential have less cost of energy and more feasibility.

5. Planning

Planning wind PV hybrid power system (WPVHPS) involves a cost-effective design on priority. The various aspects that are optimally adjusted before commencing are size, fluctuation of load and generation. But, some design considerations such as tilt angle of PV panel and a hub height of wind turbine too have importance. Besides the priority objective, when the reliability of supply is seen, the optimum number of units plays an important role. The years of service life is also important in planning. Graphical construction and probabilistic approaches in combination with an optimization method are used for planning. Planning has become a multi-objective optimization with multi-dimension.

Yang et al. [29] optimally designed wind- solar-battery system for the minimal annualized cost satisfying the limit of loss of power supply probability (LPSP). The five factors such as number PV module, wind turbine and battery units; module inclination, and height of wind turbine have been optimized by genetic algorithm (GA). The result is indicative that the minimum number of wind turbine with some batteries and PV panels with the location-dependent tilt angle is a good solution.

After going through various traditional approaches for their suitability for wind-PV hybrid systems Sinha et al. [30] suggest for using a hybrid of multiple algorithms which can remove the shortcomings of a single method. Abbassi et al. [31] discuss the battery for energy storage which is slow but super-capacitor is fast in giving away the power to the peak load. The energy management is influenced by proper sizing of these storages. The statistical probability density functions are considered for wind speed and irradiation. Discrete Fourier transform (DFT) of the output power to different fast and slow components is done. Monte Carlo simulation (MCS) for different scenarios is very useful for confirming a design for such stochastic variations of generation and load. One contribution of the storage in such system is towards the frequency management. In a similar line, Arabali et al. [32] suggest a new strategy to meet the controllable heating, ventilation, and air conditioning (HVAC) load with a hybrid-RES and ES system. From recorded weather data and load stochastic model of the wind generation, PV generation, and load are developed by Fuzzy C-Means (FCM) clustering dividing data into 10 clusters to show seasonal variations. A multi-objective GA is employed to get the optimal size, cost, and availability DC micro-grid systems with PV and wind [33]. When planned with high-temporal resolution data increased control, improved export, availability of power and decreased variability than for hourly data set. The diesel generator is initially thought as an alternate supply once power fails because it is well transferrable, standard and has a high power-to-weight ratio [2]. When various DERs are integrated into the system, these can affect the voltage profile of the system and demands frequent tap change, but if the voltage is set based on one fixed point, there may be an overvoltage at another. During planning in addition to

overall operational cost, the capacity of capacitor bank or power factor correction equipment and inverter control are also to be considered [34].

6. Operation

6.1 Energy management

Energy management system (EMS) is an integration of all the algorithms procedures and devices to control and reduce the usage and the cost of energy used to deliver the load with its specifications. In a critical review [35] it has been pointed out that, most of the EMS for RES is concerned with flow and control of power and efficient battery utilization for its durability. But, a full-fledged control approach is yet to be developed.

Wu et al. [36] proposed optimal scheduling of the PV system for saving the time-of-use (TOU) cost. Sichilalu et al. [37] focused on a net-zero-energy building by demand side management. The energy management of a grid-connected WPVHPS has been introduced in hardware [38]. In this paper, the hardware, communication and how to meet its requests and functions are emphasized. The system could manage both grid-connected mode and stand-alone mode. EMS for both standalone and grid-connected hybrid RES are reviewed by Olatomiwa et al. [39]. EMS based on linear programming, intelligent techniques and Fuzzy logic controllers is discussed for various combinations. In the study [40] an EMS for controlling end-user building loads, AC, light, ice storage discharge, with adequate solar rooftop PV systems in groups to absorb PEV penetration using practical charging situations are developed without delaying EV charging. The EMS is developed in [41] for a micro-grid with RES that checks net excess generation, battery power and SOC and takes the decision whether to charge/discharge the battery, reduce PV generation, shed load or increase generation of PV by MPPT to control load end voltage. Boukettaya et al. [42] developed a supervisory control in a MG with WPVHPS, a flywheel energy storage system (FESS). Reihani et al. [43] studied the EMS for a MW-range battery energy storage system (BESS) with actual grid data serving for peak load shaving, power smoothing, and voltage regulation of a distribution transformer.

A distributed algorithm that extracts renewable energy sources on high priority through monitor and prediction of generation and loads online is proposed in [44]. It works to reduce cost and improve system stability. In [45] reports a battery management system (BMS) based on physics-based models of lithium-ion (Li-ion) batteries and vanadium redox-flow (VRF) BESS. In [46] a VRF storage device for frequency regulation and peak-shaving tasks is demonstrated. Multiple BMSs are required in order to reach the desired capacities at grid level demand. A part of the (EMS) in order to achieve specific operational objectives is described in [47].

Gelazanskas et al. [48] review demand-side management (DSM) and DR, including incentives, non-critical load scheduling and peak shaving methods.

Vasiljevska et al. [49] demonstrated an EMS in a medium voltage (MV) network with several MGs by a hierarchical multi-level decentralized arrangement. A power management system (PMS) is proposed for a PV-battery-based hybrid DC/AC MGs for both grid-connected and islanded modes [50]. It balances the power flows, regulates bus voltage automatically under different operating circumstances.

6.1.1 Centralized control

A grid-connected hybrid system with battery is studied and tested for centralized control under three scenarios by [51]. The control strategy developed could

maximize the utilization of the hybrid system. Centralized control requires fast communication and supercomputing to handle a large amount of data in a short time. This is less reliable due to single point attack risk. A new topology of WPVHPS is proposed by Singaravel et al. [52]. In this topology, the sources are connected together to the grid via only a single boost converter—inverter setup.

6.1.2 Distributed control

It is very suitable for grid-integrated renewable sources. Alagoz et al. [53] describe that DERs are gradually increasing count with each consumer turning into a prosumer. This can take the best out of it if there is a bidirectional interaction between DERs. A service-oriented infrastructure can be formed by a tree-like user-mode network (UMN). In [54] the coordination control of a WPVHPS and a proton exchange membrane fuel cell (PEMFC) is studied. A grid-connected WPVHPS is proposed in [55]. The pitch control of the wind turbine uses radial basis function network-sliding mode (RBFNSM), and the MPPT of PV system uses general regression neural network (GRNN).

For control of the voltage and frequency at the point of common coupling firefly algorithm (FA) based proportional integral (PI), and PID controllers [56] are used. In [57] authors have shown that the modified adaptive accelerated particle swarm optimization (MAAPSO) proves better than PSO for PID and fractional order PID battery charge controller.

6.1.3 Hybrid control

This type is regarded as a combination of centralized and distributed control and is more versatile. Qi et al. [58] reviewed supervisory model predictive control (MPC) and developed it in distributed architecture taking two spatially distributed wind and PV subsystems each with storage, in a DC power grid, with a local load connected. For a WPVHPS with fuel cell, [59] a direct control scheme in a hybrid AC/DC structure is developed that deploys a harmonic virtual impedance loop and compensates voltage.

6.1.4 Control communication

Dynamic interaction between transmission and distribution systems caused due to transformations in power systems make control vulnerable. This is also happening in case of integration of renewable power plants to grid. Vision for perfect grid management can never undermine the importance of control communication. If the output of a renewable energy power plant is greater than 10% of the line capacity, temporary unavailability [60] can adversely affect power grid stability, so demands a communication. It is important to develop an intelligent, self-adaptive, dynamic and open system. So, a multi agent system (MAS) is proposed [61] to handle the energy management of the hybrid PV-wind generation system in which each agent with a RES reacts intelligently to changes.

For the energy control in a distributed manner, energy routers can serve dynamically the energy distribution in the grid, where the whole structure can be termed as energy Internet [62]. Cao et al. [63] discuss in detail energy internet called as version 2.0 of smart grids that has the two-way flow of information and power. More openness and peer-to-peer communication are introduced. This network can balance power with more interaction and options. Anticipatory or predictive control is possible based on information to anticipate future states and appropriate decision-making for timely action.

For peak load and outage, a building integrated PV (BIPV) mainly for self-feeding of buildings equipped with PV array and storage is studied in a DC MG [64]. Hierarchical control is designed by Petri nets (PNs) interface for a 4-layered EMS that regards the grid availability and user's commands. The layers are human-machine interface (HMI), prediction, cost management, and operation.

6.2 Power quality issues

The power quality is also an issue with the WPVHPS integrated. This section briefly indicates the power quality problems in grid integration. A well-written review has been brought by [65] for problems and solutions so far concerned with such system in grid-connected condition. Voltage and frequency fluctuation and harmonics are major power quality issues with a severe effect on the weak grid. Appropriate design and advanced fast control can solve it. Filters, control of PWM inverter, and droop control can be a solution to it. Kabalci et al. [66] discuss a three-phase inverter control scheme to limit total harmonic distortion within standards.

7. Case study in Indian scenario

According to the International Energy Agency, investment in renewables in India exceeded that for fossil fuel-based power generation in 2017. In India, the grid-interactive PV-wind generation of 688.42 MW is added in 2018–2019 with a cumulative of 64.5 GW till March 2019 [67]. Till the end of the financial year 2017–2018 the total RE installed was 70 GW whereas it is 79 GW at the end of the financial year 2018–2019. As displayed in **Figure 1** the latest RE update has major contributors are PV (36.2%) and wind (45.3%). A 41 MW (25 MW PV + 16 MW wind) with storage is under construction in Andhra Pradesh, India. This pilot project will work on efficient grid management through real-time monitoring of ramps, peak shifting and matching of load and generation profiles. India targets 175 GW of installed capacity from RES by the year 2022, which includes 100 GW of PV and 60 GW of wind. To this effect, India's Ministry of New & Renewable Energy (MNRE) released the National Wind-Solar Hybrid Policy in May 2016. It is framed to support large grid-connected WPVHPS for optimal and efficient utilization of transmission infrastructure and land, reducing the variability in renewable power generation and achieving better grid stability. Superimposition of wind and solar

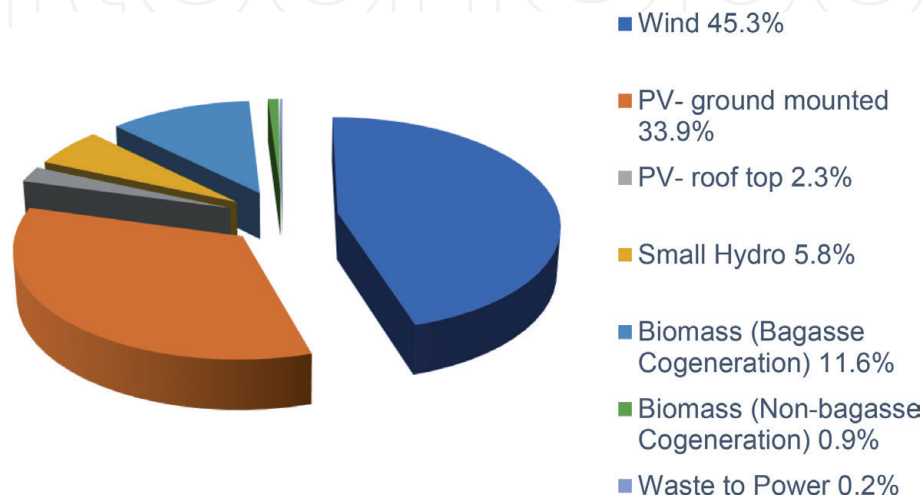


Figure 1.
Grid connected RE in India up to March 2019.

resource can complement variability of both. As per the policy, a wind-PV plant is defined as a hybrid plant if one satisfies at least 1/4th of the rated power capacity of the other. Different configurations and use of technology for AC, DC integration with storage are encouraged with incentives as specified therein.

The Central Electricity Authority is empowered to frame the standards for connectivity and sharing of transmission lines, etc. for such systems. So in India case study in hardware with grid interaction are limited to academics. A case study of Barwani, [68] found that PV-wind-battery-DG hybrid system is the most optimal solution when cost and emission are the main targets. The work in [69] involves the development of the RE based hybrid system for electricity that can supply desired power continuously throughout the year irrespective of fluctuation of energy available from standalone systems. The energy assessment has been done using Homer simulation tool for developing a small solar-wind hybrid system, at National Institute of Engineering-Centre for Renewable Energy and Sustainable Technologies (NIECREST), Mysuru, India. The WPVHPS was fully charged during the day time and thereafter the performance was checked by connecting to 596 W load through the 1500 kVA inverter and energy meter. The WPVHPS was able to supply energy for 3 h roughly in the evening.

8. Storage for RES

8.1 The case of grid-level storage

It should be noted that no ES technology claims high in all aspects. Each has its own limitation in performance when used for grid connection. System capacity, type of application and the cost of peak time electricity decide the storage capacity. A wide variety of such technology may be required to address the issues arising during grid connection.

In [70] an optimized sizing methodology for battery ES to cater peak shaving and ramp rate limiting in the power dispatch using bat algorithm and validated in a grid-connected WPVHPS to combat loss of power is presented. Five types of battery ES such as lead-acid (Pb-acid), Li-ion, flow batteries and sodium sulfur (NaS) are tested in a comparative fashion. After examining storage technologies applied in four purposes such as frequency regulation, power smoothing for wind as base load plant, power smoothing for load following and peak shaving the authors [71] have arrived in a conclusion that the power accumulation capacity is vital for frequency regulation, whereas the energy capacity influences energy intensive applications like peak shaving. The transient stability of a DG-battery-super capacitor has been carried out by [72]. Korada et al. [73] have developed a three-level grid adaptive power management strategy (GA-PMS) in MG with RES—battery-supercapacitor to support grid.

A compressed air energy storage (CAES) and wind energy system is used in [74]. It is tried to time shift wind energy to maximize the daily revenue by stochastic dynamic programming (SDP) for forecasting generation and price.

With similar objective [75] has added an approximate dynamic programming (ADP) algorithm that shows the proficiency of designing near-optimal control policies for a large number of heterogeneous storage devices in a time-dependent environment with good accuracy at par with stochastic and dynamic models when demand-variability is additionally taken. The economic feasibility of a centralized CAES is more viable than the distributed wind turbines-CAES [76].

Koller et al. [77] shows the effect of the grid-connected 1 MW BESS on frequency reserves, peak clipping and islanded operation of a MG. Grid forming and grid following inverters for the variable RES is detailed in [78]. An online

optimal operation [79] for BESS based on a mixed-integer-linear-program (MILP) is proposed over a rolling horizon window. After a detailed study of different batteries, Li-ion batteries of LFP-C type are suggested economical in long run for large capacities for stationary applications [80] with RES. The study on placement of storage by [81] indicates that the line-flow limits have a significant effect. Hybridizing PV-wind with micro-hydro power plants into a single mini-grid has been practically applied in Nepal [82] which has increased the reliability and meets the load in an environment-friendly way.

A study on grid-level FESS [83] showed that locating it at the transformer and higher levels in the grid will reduce its size by inherent power smoothing by the pool. The ability to exchange power with neighboring grids, load shifting and storage can deal with high penetration of renewable [84]. Peak shaving can be dealt with by gas powered generation and load leveling (flat profile) by coal-fired or battery or pump storage [85].

Williams et al. [86] put forth DSM by adding heat pumps and thermal storage to PV that adds on energy independence of the house.

8.2 Battery energy storage technology and materials

A battery ES with its own specific features can serve a particular usage when time, space, portability and size are some of the factors. This section reviews battery ES in view of the latest technologies, advantages, sizing, efficiency, price, and life cycle assessment.

The modern storage technologies with regard to wind power integration are discussed in [87] on which the planning rests upon. Output power smoothing operation by single or multiple ESS considering influencing factors as above is done. In the work [88], has cross-compared with the maturity level of the technology of storage.

Wide variety of storages have been detailed in [89] taking an in-depth study of the electrochemical properties of the BES. The energy capacity and the self-discharge or capacity fade of BES systems affect the suitable storage duration. Study in [90] has shown that BES can go forward for ancillary service if its cost reduces. Palizban et al. [91] have pointed out that a hybrid of different energy storages can serve multiple purposes in a cost-effective way. In [92] the technical viability of Li-ion batteries for the inertial response (IR) in grids with ample contribution of wind power has been evaluated.

One particular BESS cannot suit for all the support services like short, medium as well as long term [93]. Only Li-ion can serve for short duration support. For distributed storage and medium duration support, Pb-acid and Li-ion batteries are most suitable. A lithium-antimony-lead (Li-Sb-Pb) liquid metal battery is proposed by [94] which has higher current density, longer cycle life and simpler manufacturing of large-scale stationary storage systems.

8.3 Plug-in hybrid electric vehicles (PHEV)

RE can be better absorbed if electric vehicle charging and discharging is done strategically. Conventional power supplies can be sent as needed to match demand and provide ancillary services for grid stability. Contribution to grid by RES is increasing although these sources are intermittent by nature. This is now an operational challenge to balance the intermittency of RES. Electric vehicles (EVs) offer a scope to manage demand and potentially mitigate the amount of curtailed energy by controlling when EVs are charged.

Different types of charger such as AC/DC, slow/fast are discussed in European standard by [95]. Integration of ESSs in EVs charging station has grown with AC

but the DC system has higher energy efficiency with improvement up to 10% [96] with less number of conversion stages taking generation from RES. The important communication system, not less than the brain makes it all possible in a coordinated manner. It communicates with the smart metering system present on the MG and on the EV charging station, through Modbus on TCP/IP connection, using the internal LAN, and with the ES converters, through the CAN protocol.

When the market penetration of uncoordinated plug-in electric vehicles (PHEV) is studied by [97], it is encouraged for load control by smart charging. It can reduce the size of central storage devices.

Clement-Nyns et al. [98] have investigated charging and discharging of PHEV in a cooperative manner that helps the voltage control and reduces congestion.

The PHEVs as dynamically configurable dispersed storage can operate in vehicle-to-building (V2B). Based on the distinctive attribute of the battery, the benefits of using PHEVs as energy storage for DSM and outage management are deliberated by Pang et al. [99]. The faster-charging are yet to come up. The parking time can be utilized for charge or discharge mode when required.

9. Long-distance transmission

All countries emphasize on use of clean and alternate energy. As discussed in previous subsections, with the rapid development of RES fresh set of technological requirements pops up on the grid: the location of RE resources distant from load centers, and the power-variability. The characteristics and its control of the electricity grid need a modification to integrate RE [100]. At present many countries lack affordable storage facilities for renewable power. But on a positive note, the excess power is transmitted through the national grid by internal transmission lines. However, connectivity to the national grid should be even or balanced. The large scale intermittency demands to switch in fast-acting conventional reserves on the basis of climatic forecasts on short to long time frame; by setting up grid-scale storage or; by long-distance transmission of RE generation connecting to larger reserves for resources in order to equalize regional and local surplus or shortfall. This section discusses opportunities for renewable energy transmission over a long distance.

Long-distance transmission capacity is necessary to despatch a huge quantity of renewable power a thousand kilometer or more across the country. The construction of transmission tower is given low priority by historically low investment in transmission, community concern over the required right of way in more dense urban areas. Further many long transmission lines are aged and of inadequate capacity. Both remote solar PV and wind energy generation require “Green power Superhighways.” HVDC transmission [100] and use of superconductors [100] are costly alternatives as RE itself cost more to the user. HVDC lines offer transient as well as short term voltage stability. Variability of the source can be well managed via an extensive and robust transmission line network. The transmission capacities based on power electronics devices starts to change the grid characteristics and control requirements. The key power electronic technology has a high impact on the power quality because of its fast control and sensitivity to fault and other abnormal conditions of the grid.

So, research is still going on HV superconducting cable for long-distance transmission of RE [101]. Anyway, in the present day of renewable energy, the grid has to serve national character. With more urbanization and industrialization, the reduction of carbon dioxide emission has been essential and requires long-distance delivery of renewable power [102]. Rooftop PV can reduce the need for long-distance transmission, but have a higher cost than wind or concentrating

solar power, and with small but considerable esthetic sense. The gradual entry of big wind and solar generation demand huge spending of money in improving the capacity and efficiency of long-distance electricity transmission.

Many researchers feel till date that there is a growing gap between the grid system and control technologies and power electronics equipment design capability.

10. Conclusion

Renewable energy is environmentally, socio-ethically and economically sustainable compared with the dominant centralized and non-renewable energy generation systems. However, the techno-economic limitations for ever-growing renewables' share of power generation in the majority of the countries are alike.

The RES is not currently cost-competitive with base load coal-fired power, and geographically dispersed. However, it leads over a conventional generation in low emissions of air pollutants, free fuel, and a low gestation period.

Traditionally, the electric power system is not intended to handle RE generation and storage. But with the rapid growth in the alternate energy sector, the integration of the DE and RES into an electric power grid can be done in many ways along with power quality solution. The power electronic technology plays a significant part in the integration of RES into the electrical grid. They offer exclusive competence over conventional interconnection technologies. They further provide additional power quality and voltage/reactive power support.

This chapter describes the various aspects of grid interface for wind energy systems and solar PV systems and some other DERs for electrical system compatibility by reducing the effects on fault, and flexibility in functioning with various other DERs, while minimizing the interconnection costs.

Around 100 research papers in various problems of grid connection have been surveyed but claims in no way to be complete. This particular subject is definitely emerging in nature and attracts many researchers towards it.

It has been discussed that utility RE investments are typically evaluated from regulatory, project finance, and engineering viewpoints. The regulatory evaluation focuses on ensuring utility conformance to RES and that expenses are kept judiciously limited. From a finance perspective, the return on the investment within disjunctive limits of the funding and cash flows for a particular project is evaluated. The technical evaluation determines the engineering and operational safety of the project and the specific technologies deployed. While these approaches are essential for investors, utilities, regulators and ratepayers, they do not scope out the goodness that a RES can convey beyond the boundaries of a given project, such as the usefulness of transmission and storage and the organizational plus point of bringing an integrated grid.

Variability of RES occurs due to the nature of the climate. Thereby the uncertainty in the generation is affecting up to 70% of day time solar capacity due to passing clouds, and 100% of wind capacity on calm days, is much greater than the somewhat expected variations of a few per cent in demand that system operators handle. This has been discussed. It necessitates a more complicated voltage and frequency regulation. The larger the RE entrant, the more complicated (sometimes unattainable) is the management of this challenge.

Spatial aggregation of RES greatly lessens forecast errors, just as it lessens variability. This may be due to spatial smoothening effect. The forecast error rises further as the time range of the forecast is expanded. Forecasting techniques are improving constantly. But this requires better weather model and better data collection and processing.

In contrast to the convention fossil fuel power sources, selecting a site to exploit certain RES has few or no degrees of freedom. In other words, RE such as wind and PV, are site-constrained. Transmission needs to be extended to these sources, not the other way around. Future distribution systems will contain MGs and hence it is necessary to understand the steady-state and transient operating conditions of such systems to appraise their effects on the present grid.

Control system is the key element for flexible operation, high efficiency and superior power quality in RE integration. In this regard, the control system fetches real-time states through local measures and via the communication, takes actions to attain the control objectives (for instance, maximum power extraction, output voltage and frequency regulation, reactive power compensation, etc.), and at last send commands to the actuators, usually power electronic converters. Challenges in control design and realization, energy management strategies, communication layout and protocols, and topologies for power electronics-based distributed RES are all addressed in brief here.

The value of energy storage by batteries in grid-level applications that guides both transmission and generation services to the grid. It mitigates the unpredictability of generation. It has been emphasized to conduct a review of the technological potential for a range of battery chemistries.

Lastly, it is reiterated again that because of some demerits and irrevocable externalities in conventional energy production, it has become essential to go for and uphold technologies and insist for RES. Power generation using RES should be enhanced in order to reduce the per unit price of generation.

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